



Preliminary Computational Assessment of Disk Rotating Detonation Engine Configurations

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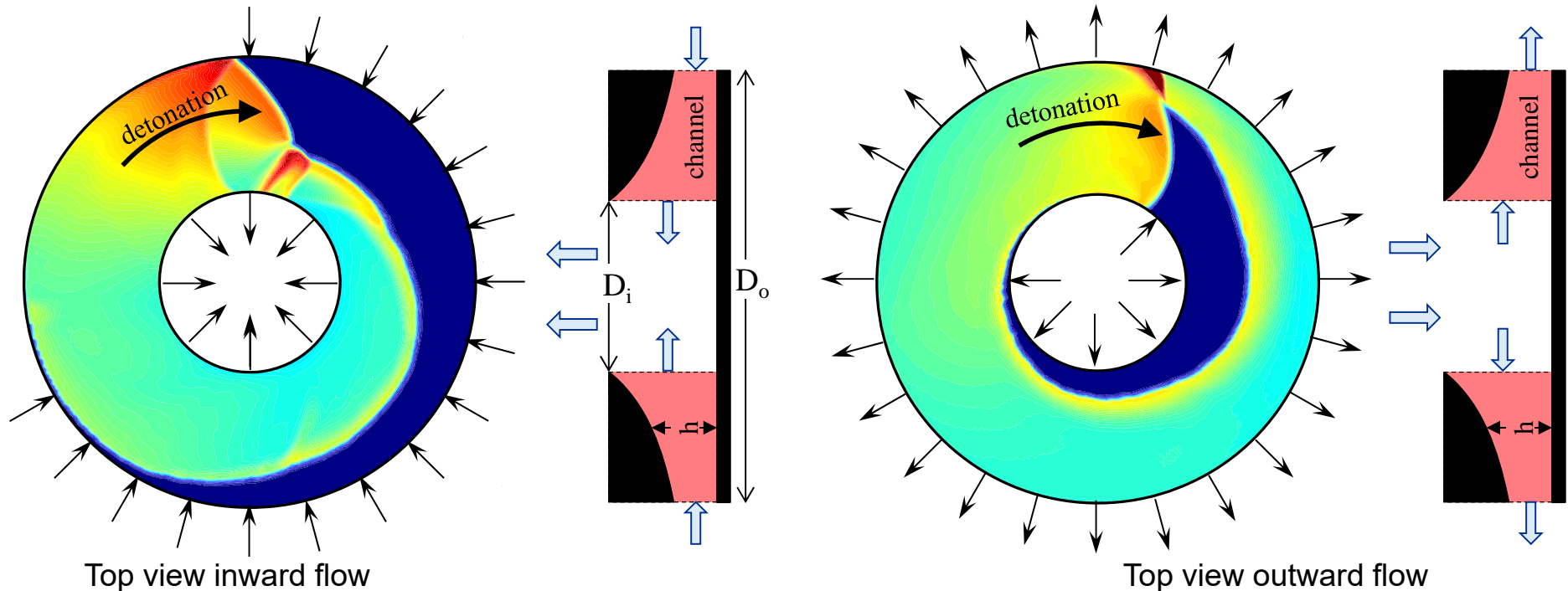
Outline

- Background
- Modeling Approach
- Simple Tests
- Results
- Concluding Remarks



Background

The Pressure Gain Combustion Community is Investigating Rotating Detonation Engine (RDE) Configurations Where Flow is Radial



- Inward and outward flow scenarios are of interest
 - Axially Compact
 - May match well with radial turbomachinery
- May enhance detonative cycle performance
 - Centrifugal forces may be of benefit

Fast, Flexible Simulation Capability Is Needed to Assess Potential



Modeling Approach

Use the Same Q2D Euler Solver Currently Employed for Annular RDE's
(Distr. C Released LEW-19488-1)

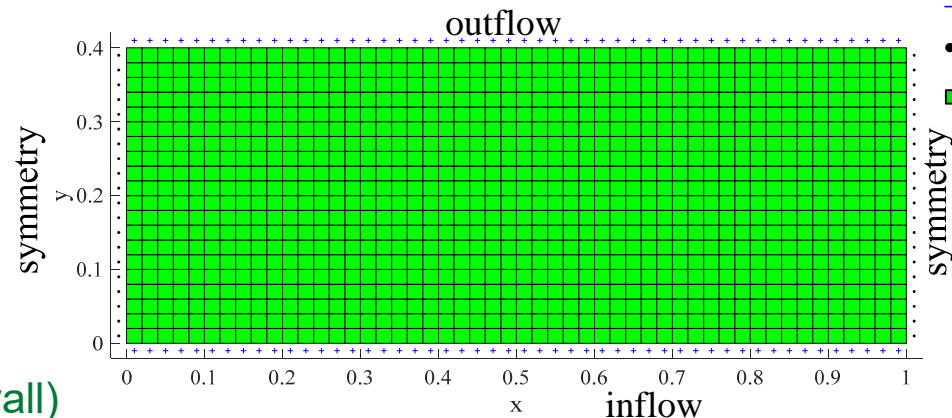
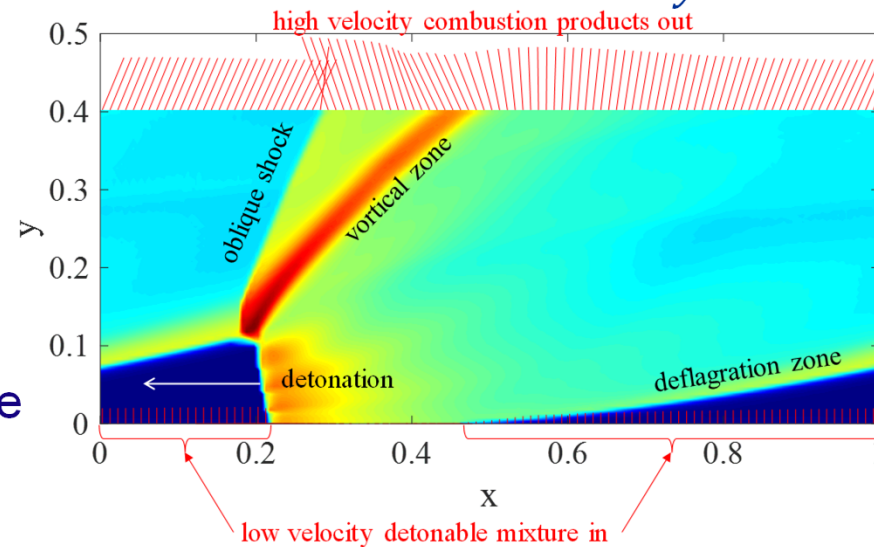
Attributes

- Calorically Perfect Gas
- Premixed
- Detonation Frame of Reference
- Source terms model:
 - Chemical reaction
 - Q2D area variation
 - Viscous effects
 - Heat Transfer
- High resolution numerical scheme
- Boundary conditions
 - Sub or supersonic exhaust flow
 - Inlet flow restriction loss model
 - Inlet backflow allowed

For Present Study

- Adiabatic
- Inviscid
- Boundary conditions
 - No inlet backflow allowed
(notional check valve, aka, a wall)

$$\frac{\partial h_w}{\partial t} + \frac{\partial h_F}{\partial x} + \frac{\partial h_G}{\partial y} = \underline{S}$$



- + y-ghost cell
- x-ghost cell
- interior cell



Modeling Approach

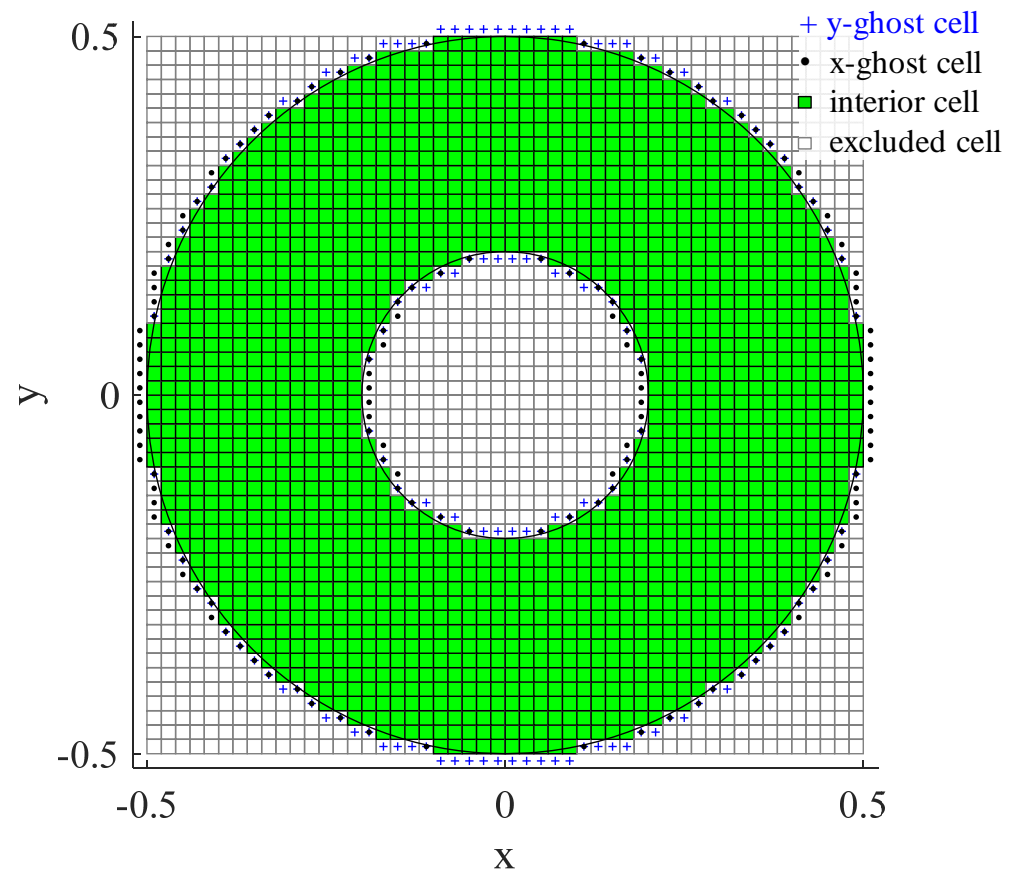
Q2D Solver Modified for Disk (Radial) Configurations

Benefits:

- Regularly spaced Cartesian grid keeps code simple and fast (runs in minutes on a laptop)
- Useful for basic parametric studies
- No core code development required

Challenges:

- Requires laboratory frame of reference
- Shocks at high skew angles to grid
- Boundary conditions are required in both x and y directions
- No easy symmetry conditions
- Boundary cells (aka, ghost cells) are not regularly spaced
- Inflow boundaries require that flow is radial (much algebra in a Cartesian system)
- Check-valve (aka wall) boundary condition requires no flow normal to a boundary tangent
- Boundary surface areas are $> \pi d$
- No analytical 'test cases' to validate



Challenges Are Mostly Bookkeeping
Approach is Sound

Modeling Approach Tests

Non-Reacting Shock Induced Inflow

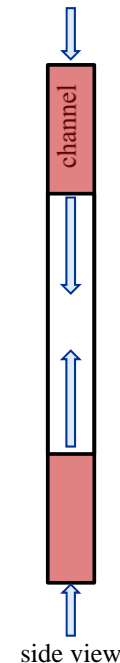
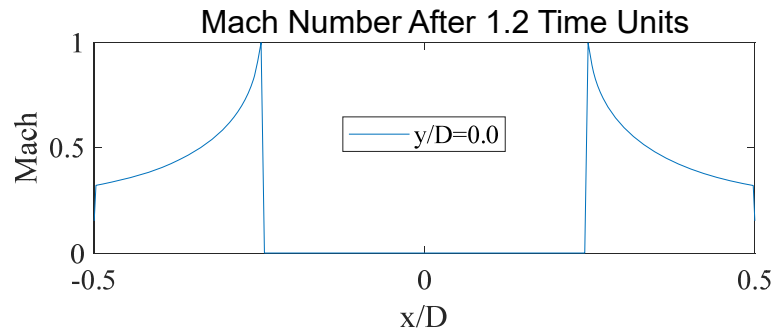


Setup

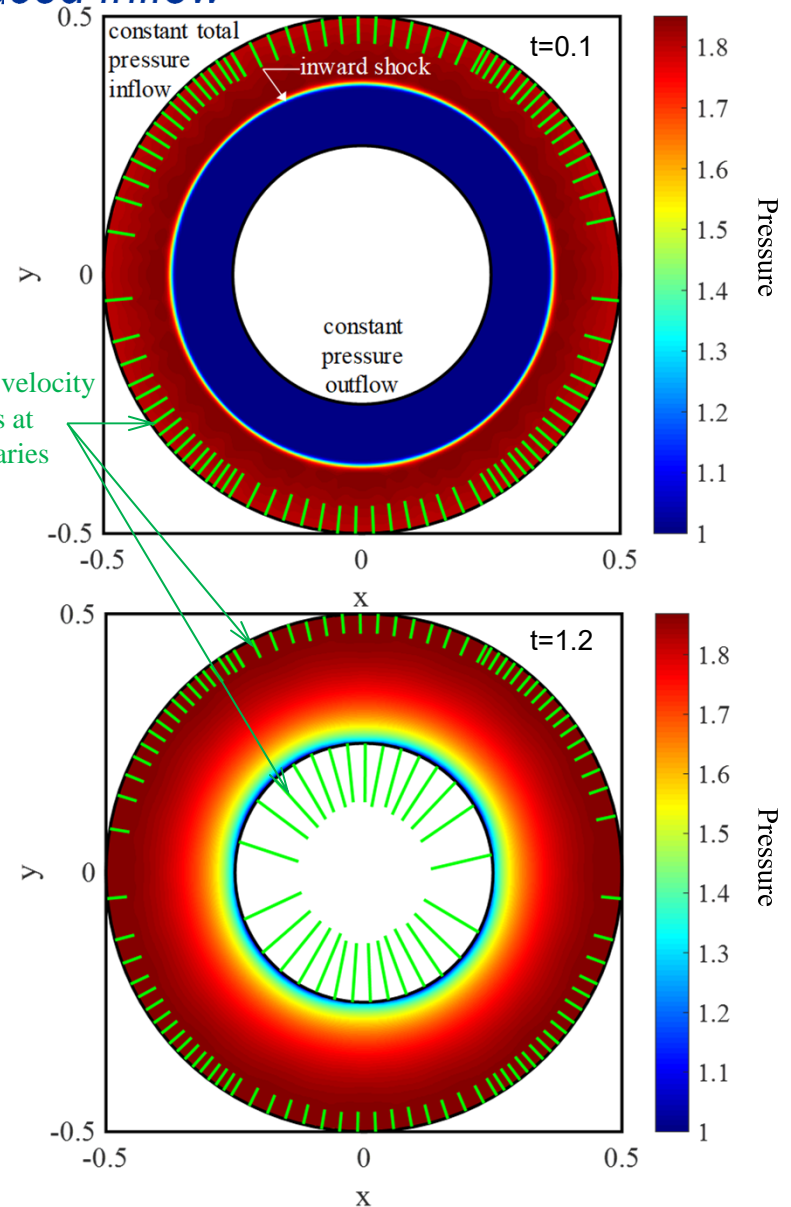
- 200 X 200 grid – no height variation (parallel plates)
- Radial inflow at outer diameter; constant pressure at inner diameter
- $p, \rho, u, v, z = 1, 1, 0, 0, 0$ everywhere
- Inner diameter $p=1.0$; Outer manifold $p=2.0$, $T=1.03846$
- Simulation time = 1.2 units

Results

- Initial shock wave speed correct
- Inflow and outflow mass flow rates match after 1.2 units
- Inflow is radial (on a Cartesian grid!)



scaled velocity vectors at boundaries



Inflow Boundary Condition Routines Work

Modeling Approach Tests

Simple H₂/Air One-Shot Detonation

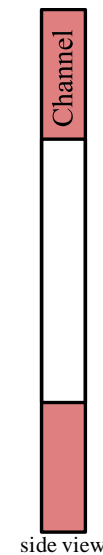


Setup

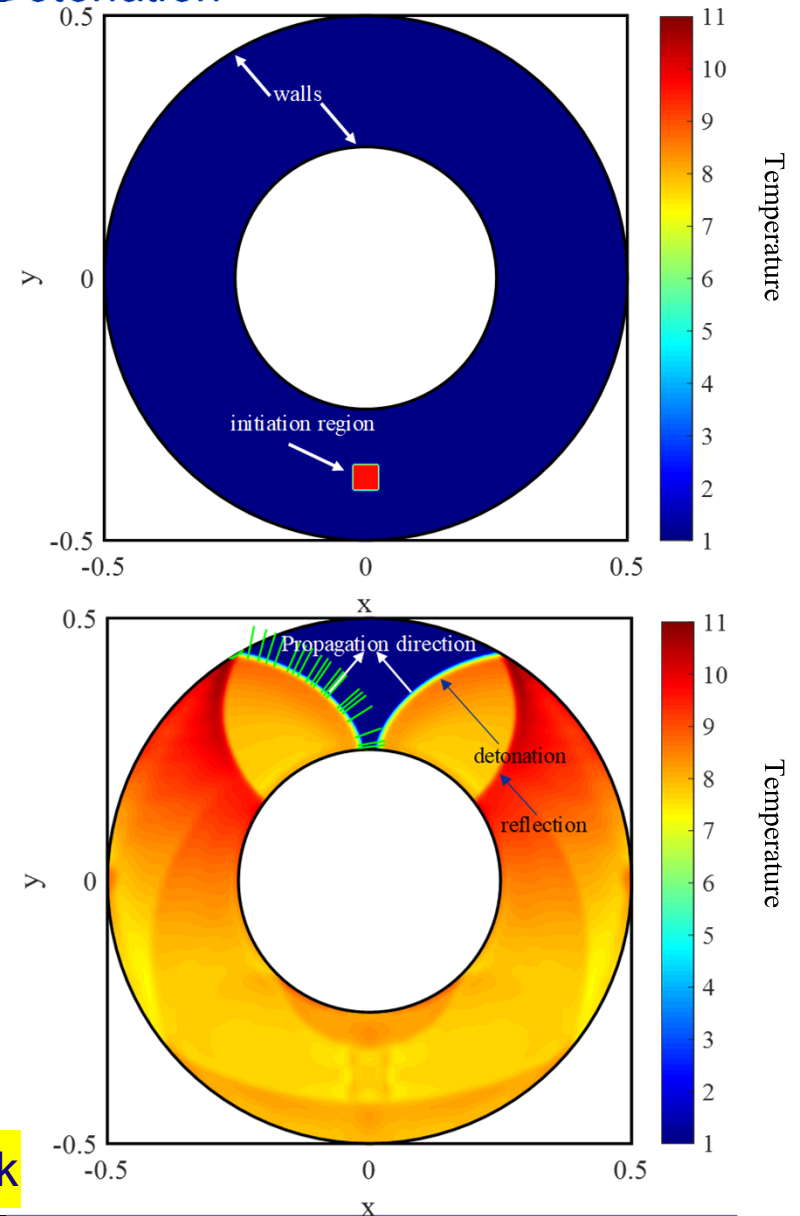
- 200 X 200 grid – no height variation (parallel plates)
- Walls at inner and outer diameter
- Initial state (non-dimensional):
 $p, \rho, u, v, z = 1, 1, 0, 0, 1$ everywhere except in a square at bottom of disk where
 $p, \rho, z = 17.0, 1.745, 0.0$
- Simulation time is 0.205 units

Results

- Detonation speed nominally matches CJ speed at average diameter
- Curvature of detonation and uniform angular velocity indicate circumferential velocity is different everywhere
- Local propagation direction correct
- Laboratory frame of reference works



side view



Reaction Model and Wall Boundary Conditions Work



Results

All Simulations Use:

- 200 X 200 Grid
- Stoichiometric H₂/Air
- Boundary Conditions:
 - Inlet manifold $p_m=4.0$, $T_m = 1.03846$
 - Outlet $p = 1.0$
 - Inlet Check-Valve (no backflow)

Exit Plane Performance Metric Used:

- Entropy Equivalent Pressure (EEP)
 - Evaluate mass-flux averaged total temperature, \bar{T}_t
 - Evaluate mass-flux averaged entropy, \bar{s}
 - Calculate total pressure which yields \bar{s} at \bar{T}_t
 - Mass-flux averages performed over one wave revolution
- Pressure Gain, $PG=EEP/p_m-1$

$$\bar{\phi} = \frac{\sum_{k=1}^{t_{\text{cycle}}/t_{\text{output}}} \left[\sum_{i,j=\text{exit}} \phi_{i,j} \rho_{i,j} U_{i,j}^n \right]_k}{\sum_{k=1}^{t_{\text{cycle}}/t_{\text{output}}} \left[\sum_{i,j=\text{exit}} \rho_{i,j} U_{i,j}^n \right]_k}$$



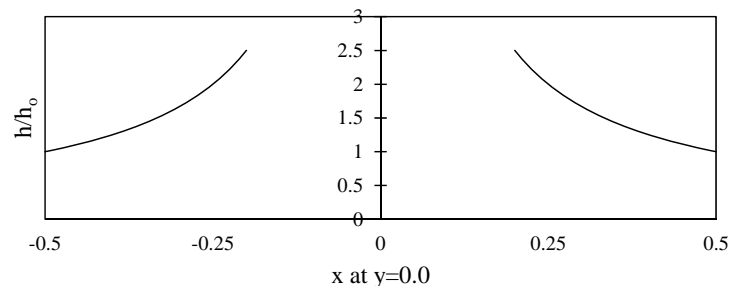
Results: Ideal Operation

Setup

- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 1.0$;
- Video shows 4 detonation revolutions; started after 5-7 wave revolutions

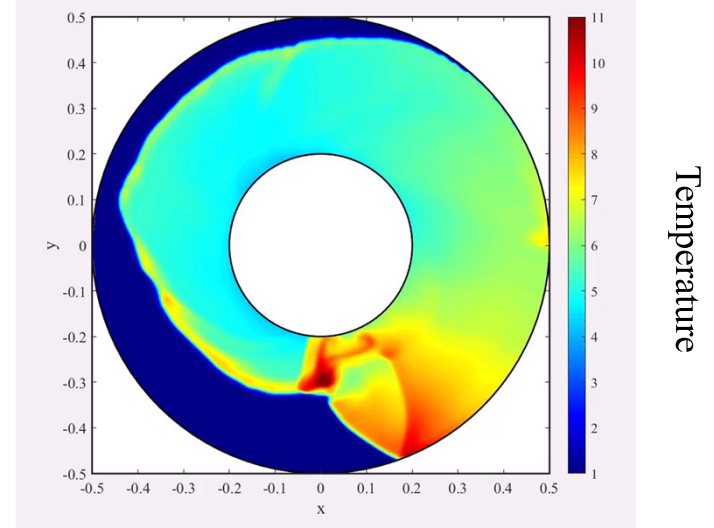
Outcome

- Detonation are both unstable and ultimately fail
 - Radially inward is distorted
 - Radially outward is eccentric
- Annular RDE is stable with these lossless boundary and conditions

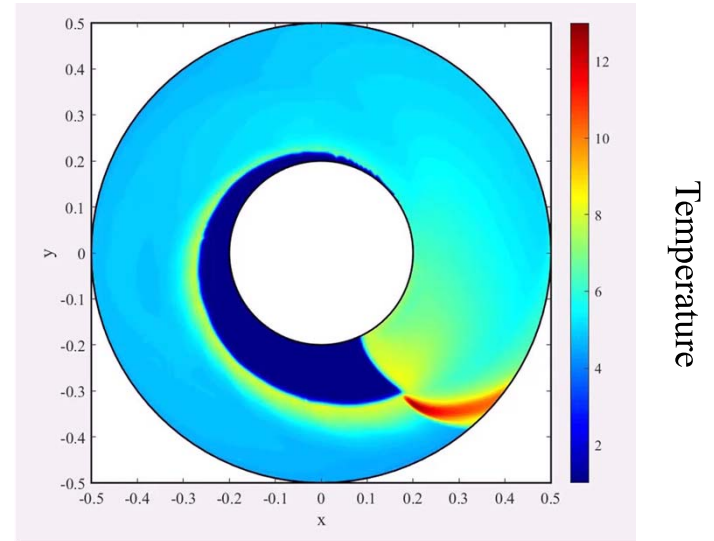


DRDE's Aren't Like Annular RDE's!

Radially Inward Video Showing 4 Detonation Revolutions



Radially Outward Video Showing 4 Detonation Revolutions





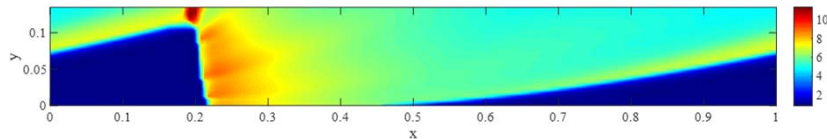
Results: Radially Inward With Inlet Restriction

Setup

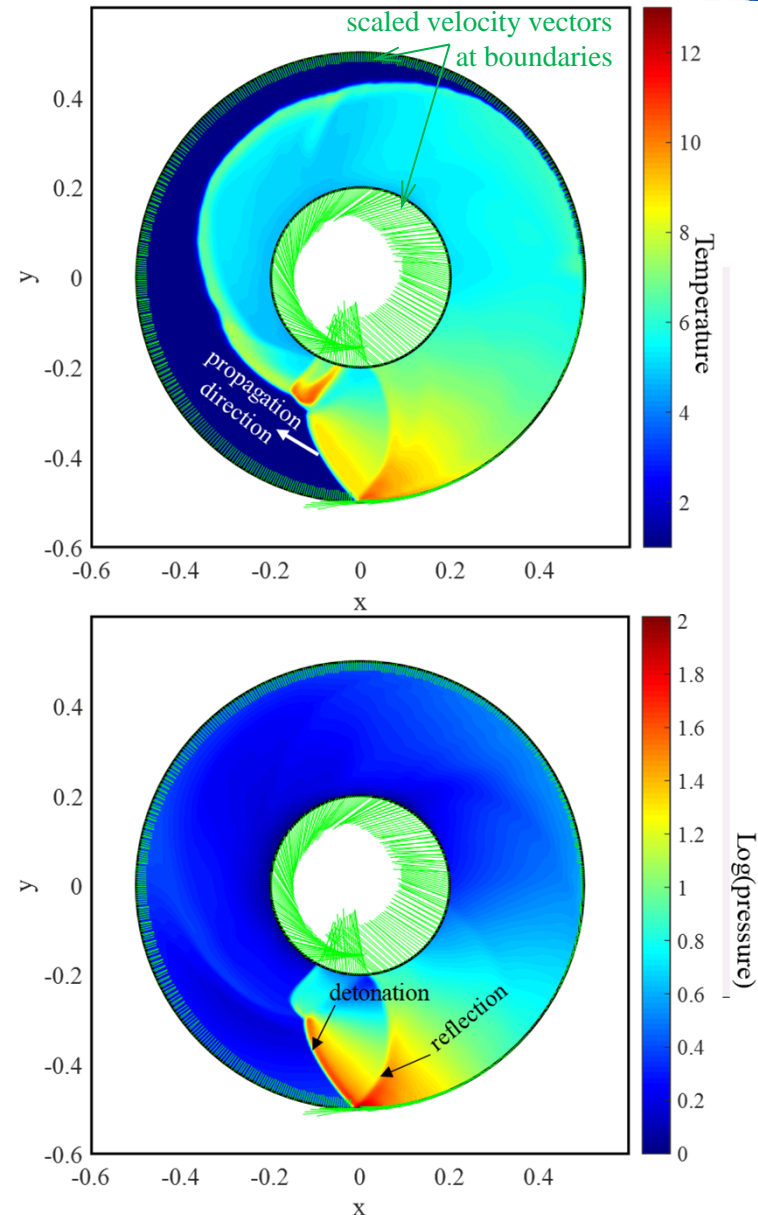
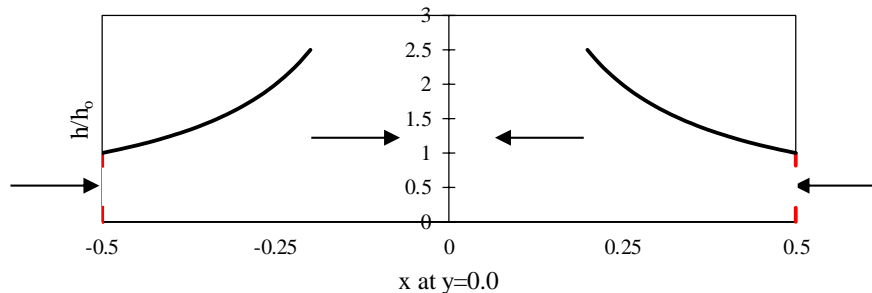
- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed 24% above CJ based on OD
- PG=90%
 - Equivalent length annular RDE PG=71%



- Exit flow could be a challenge for guide vanes or nozzle



Adding Inlet Restriction Stabilizes Flow Field



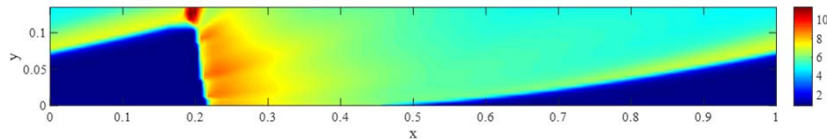
Results: Radially Outward With Inlet Restriction

Setup

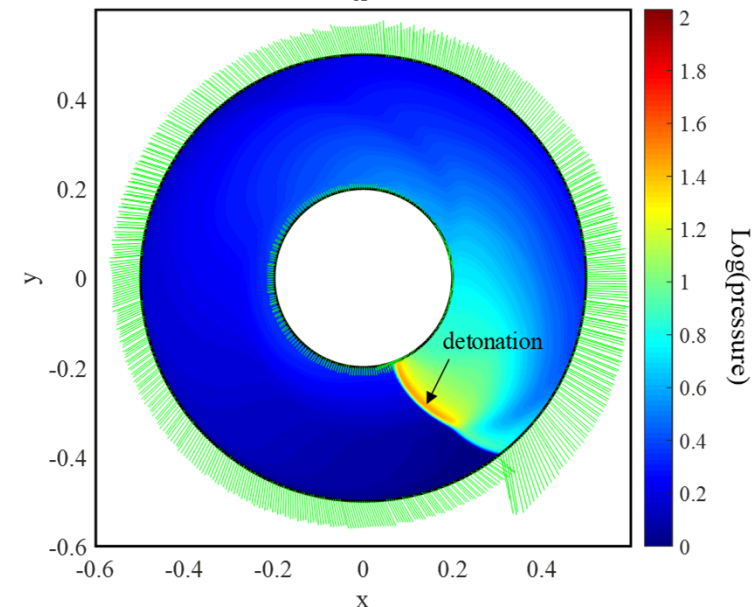
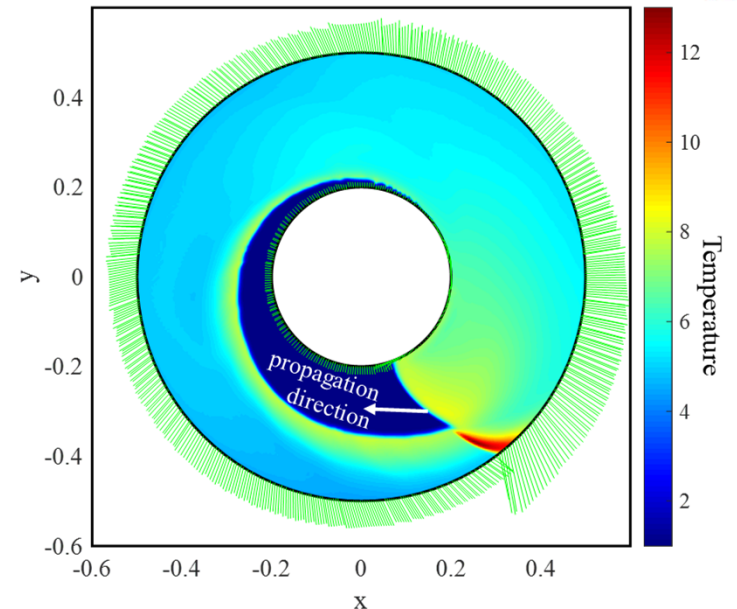
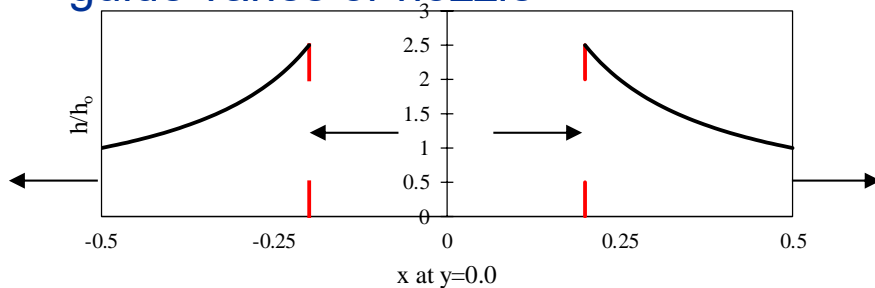
- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed 35% below CJ based on ID
- PG=65%
 - Equivalent length annular RDE PG=71%



- Exit flow could be a challenge for guide vanes or nozzle



Adding Inlet Restriction Stabilizes Flow Field



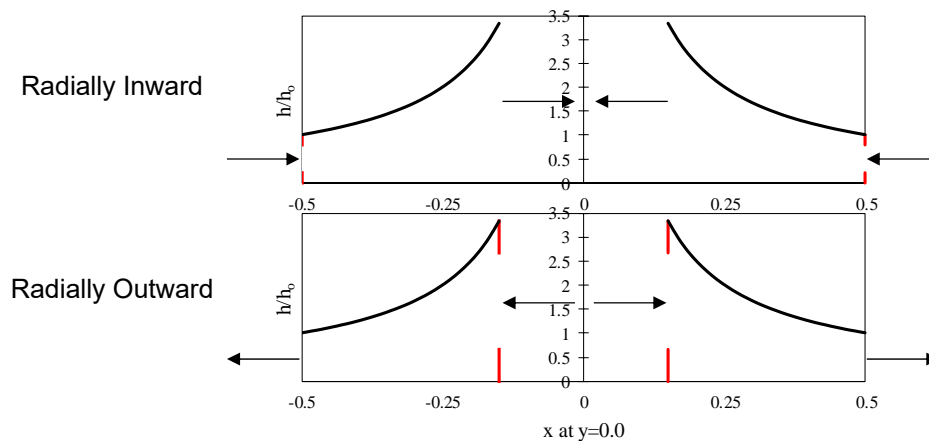
Results: Reduced Diameter Ratio

Setup

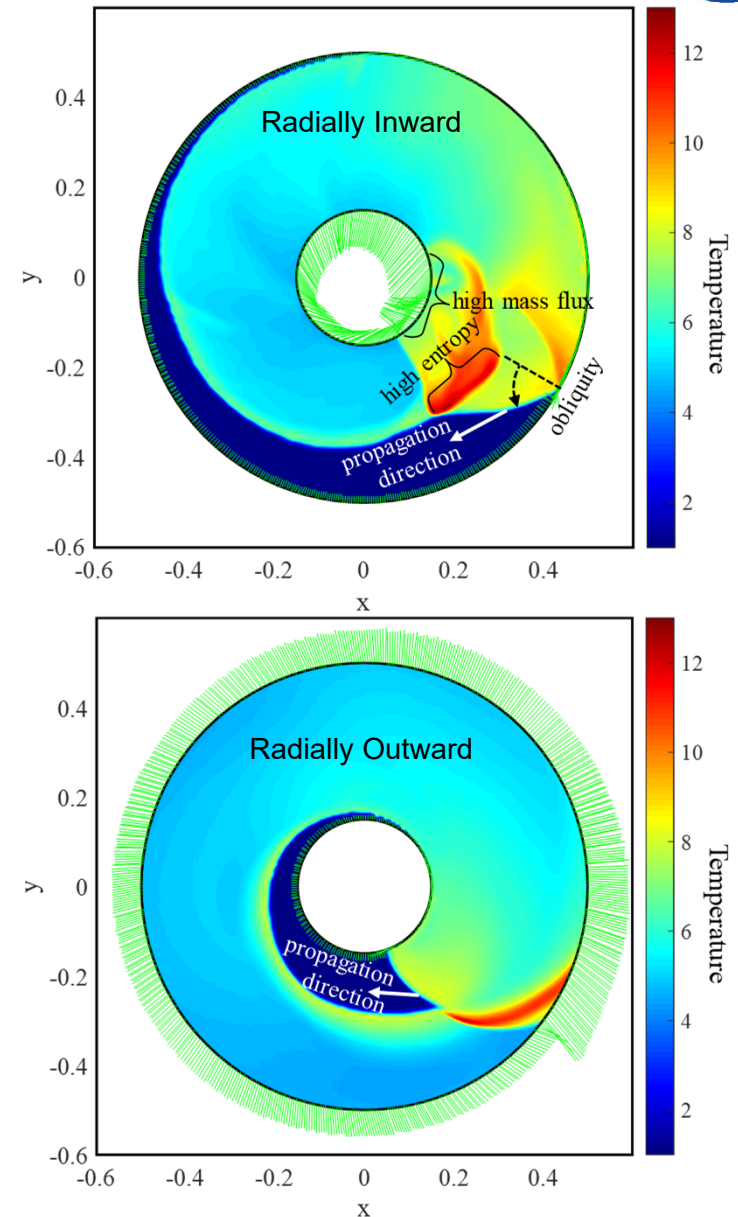
- Grid-height variation keeps area constant
- $D_i/D_o = 0.3$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed:
 - Inward: 43% above CJ based on OD
 - Outward: 39% below CJ based on ID
- Pressure Gain
 - Inward PG=66%
 - Outward PG=65%
 - Equivalent length annular RDE PG=68%



No PG Benefit From Reduced Diameter Ratio





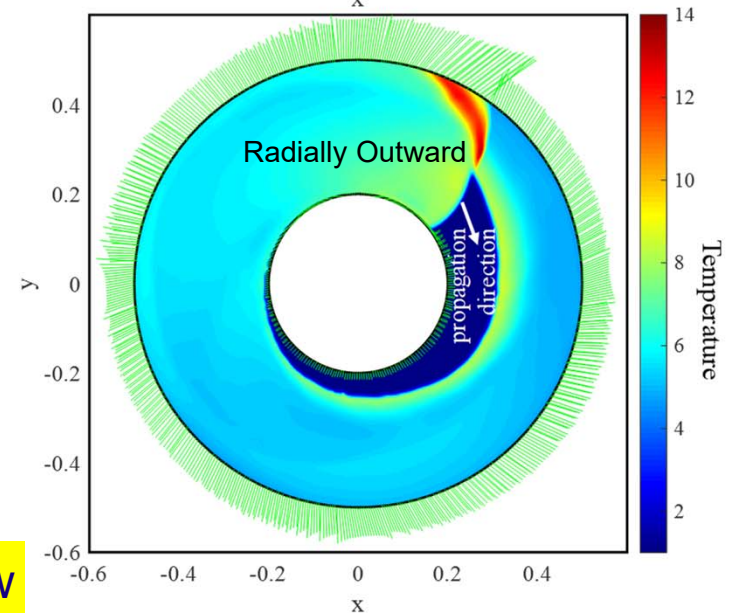
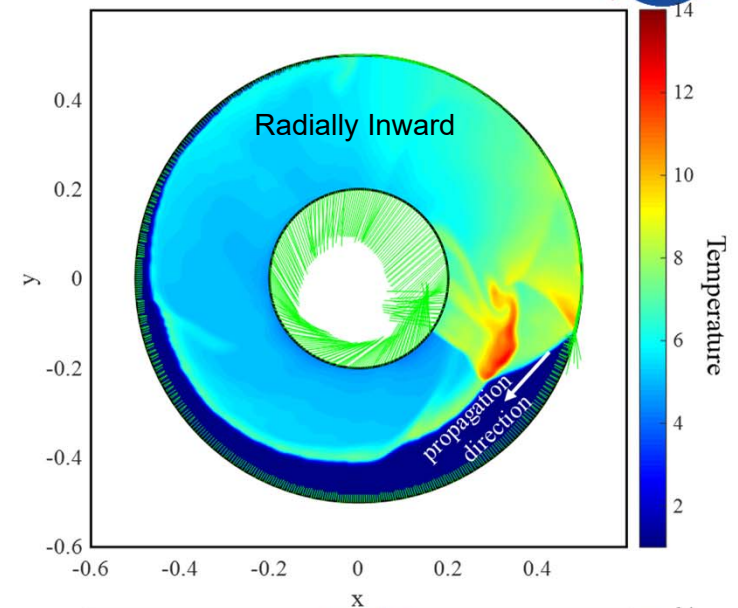
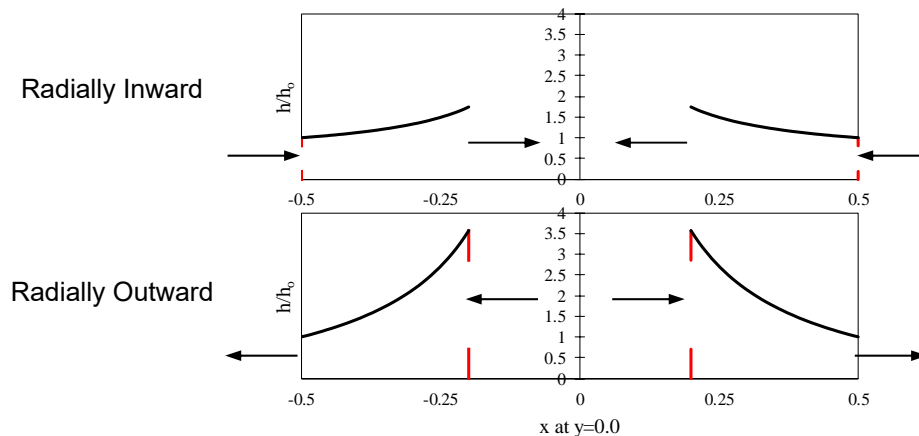
Results: Cross-Sectional Area Reduction

Setup

- Linear area reduction from inflow to outflow
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed:
 - Inward: 27% above CJ based on OD
 - Outward: 34% below CJ based on ID
- Pressure Gain
 - Inward PG=142%
 - Outward PG=105%
 - Equivalent length annular RDE PG=140%



PG Benefit From Reduced Exit Area for Inward Flow



Concluding Remarks

- Disk RDE configuration successfully simulated using modified NASA simplified Q2D code
 - A good platform for parametric studies
- Results are not yet validated with experiments; however, they conserve mass and energy appropriately, and they make sense
- Flow field is quite different from annular configurations
- Based on idealized inlet (i.e. no backflow), adiabatic, inviscid flow, and Entropy Equivalent Pressure method:
 - Radially inward configurations perform better than conventional annular configurations
 - Radially inward configurations generally perform better than radially outward configurations
 - Larger D_i/D_o configurations perform better
 - $A_{\text{exit}}/A_{\text{ch}} < 1$ (i.e. an exit throat) yields better performance
- Next steps
 - Add inlet backflow model
 - Activate heat transfer and friction models
 - Validate using Air Force Research Laboratory Data
 - More parametric optimization
 - Investigate practical nozzles and guide vanes for thrust and work extraction

DRDE's Are A Promising Configuration That Warrants Further Study



Acknowledgement

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